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(19) (CA) **CANADIAN PATENT** (12)

(54) Conductively Heating a Subterranean Oil Shale to Create
Permeability and Subsequently Produce Oil

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(57) 11 Claims

Canada

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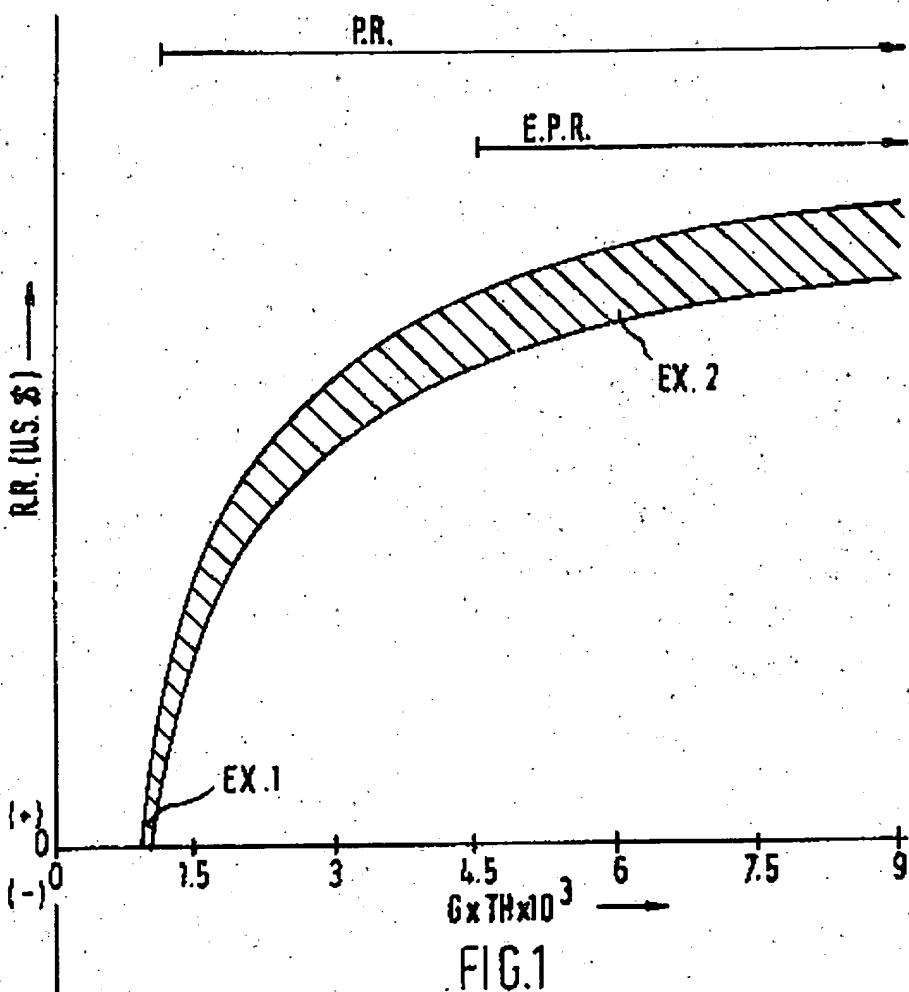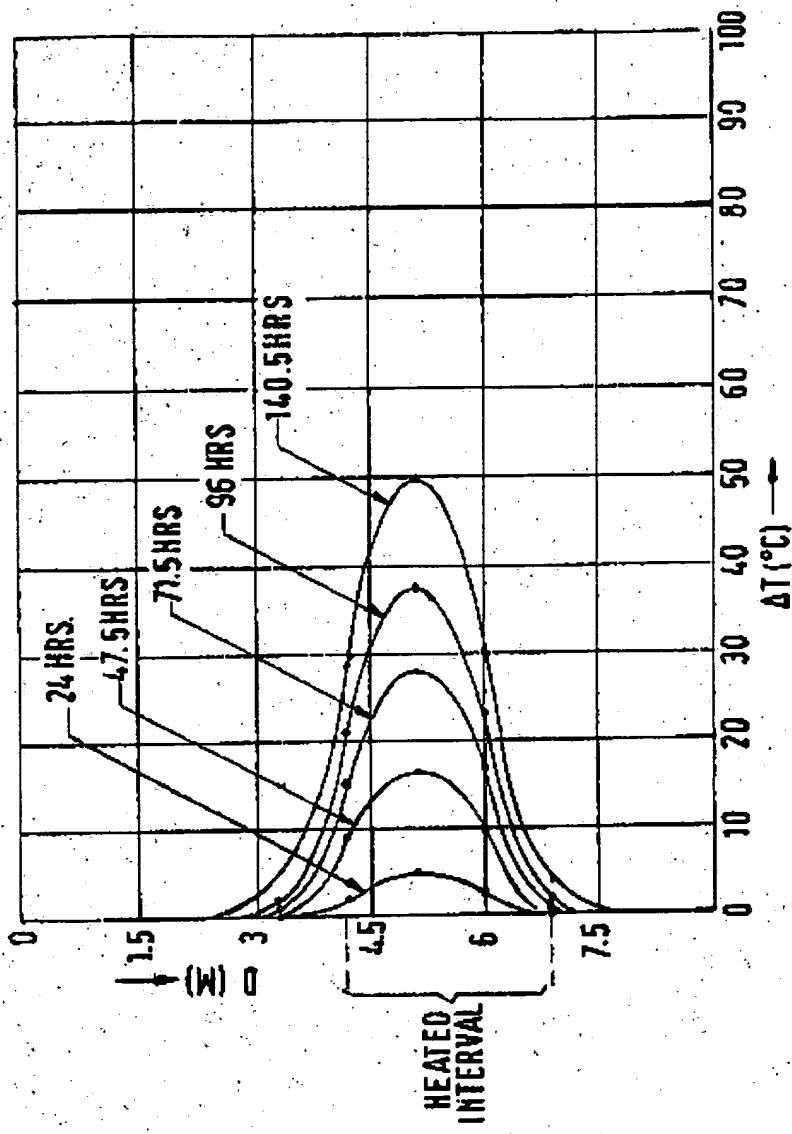
FIG.1

FIG.2

FIG.3

FIG.4

PARALLEL TO BEDDING

PERPENDICULAR
TO BEDDING

FIELD
DATA

T(×10⁻³CAL/CM-SEC°C)

T(C°)

FIG.5

FIG 6

T [°C] ↑

800 750 700 650 600 550 500 450 400 350 300 250 200 150 100 50 0

HEATERS

I₂   I₃

ΔL

I₁   I₂

I₁

3 MONTHS

20 DAYS

I₃

I₁

ΔL = DISTANCE FROM I₁–I₃(M) ——

0   0.3   0.6   0.9   1.2   1.5   1.8   2.1   2.4   2.7   3
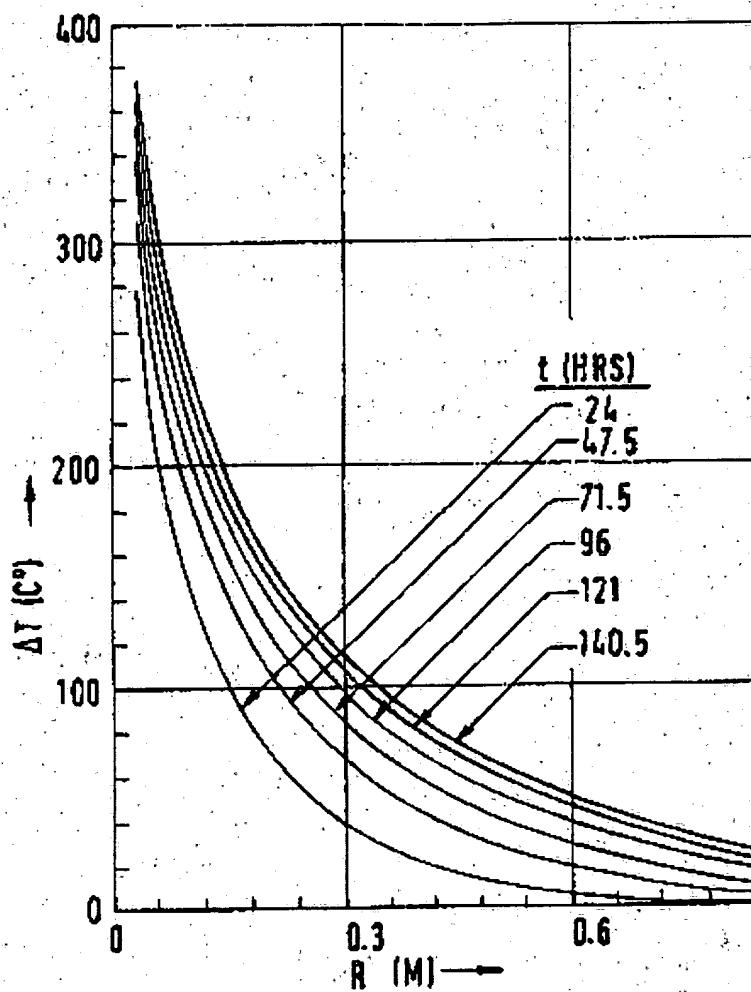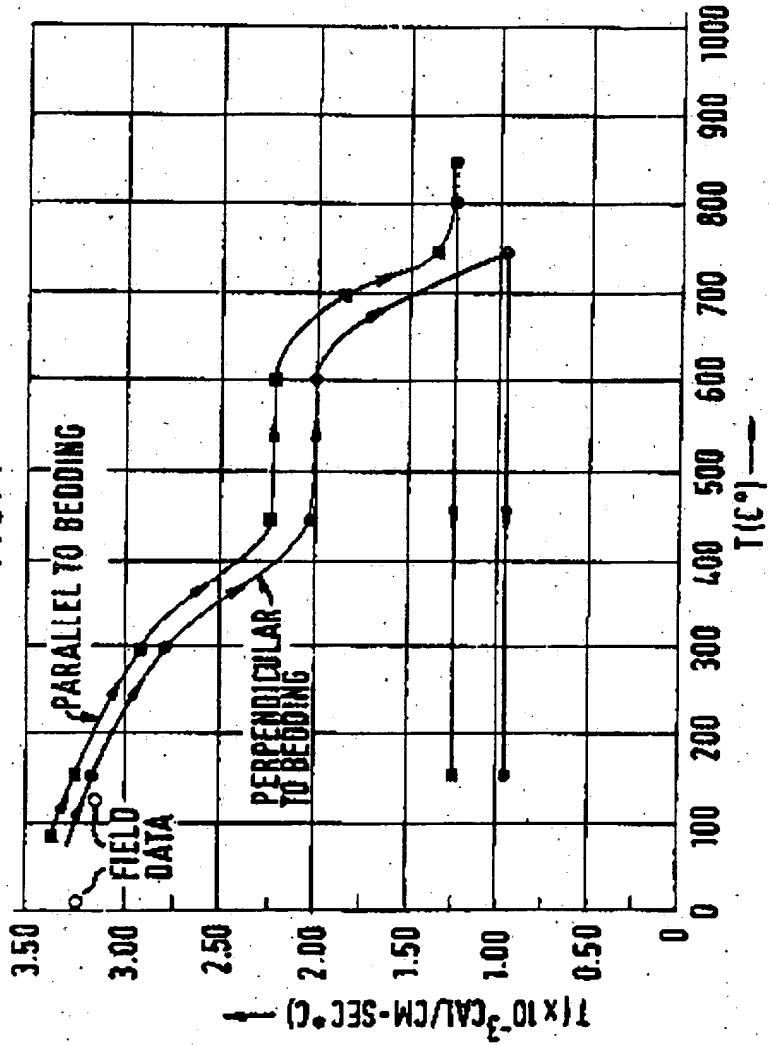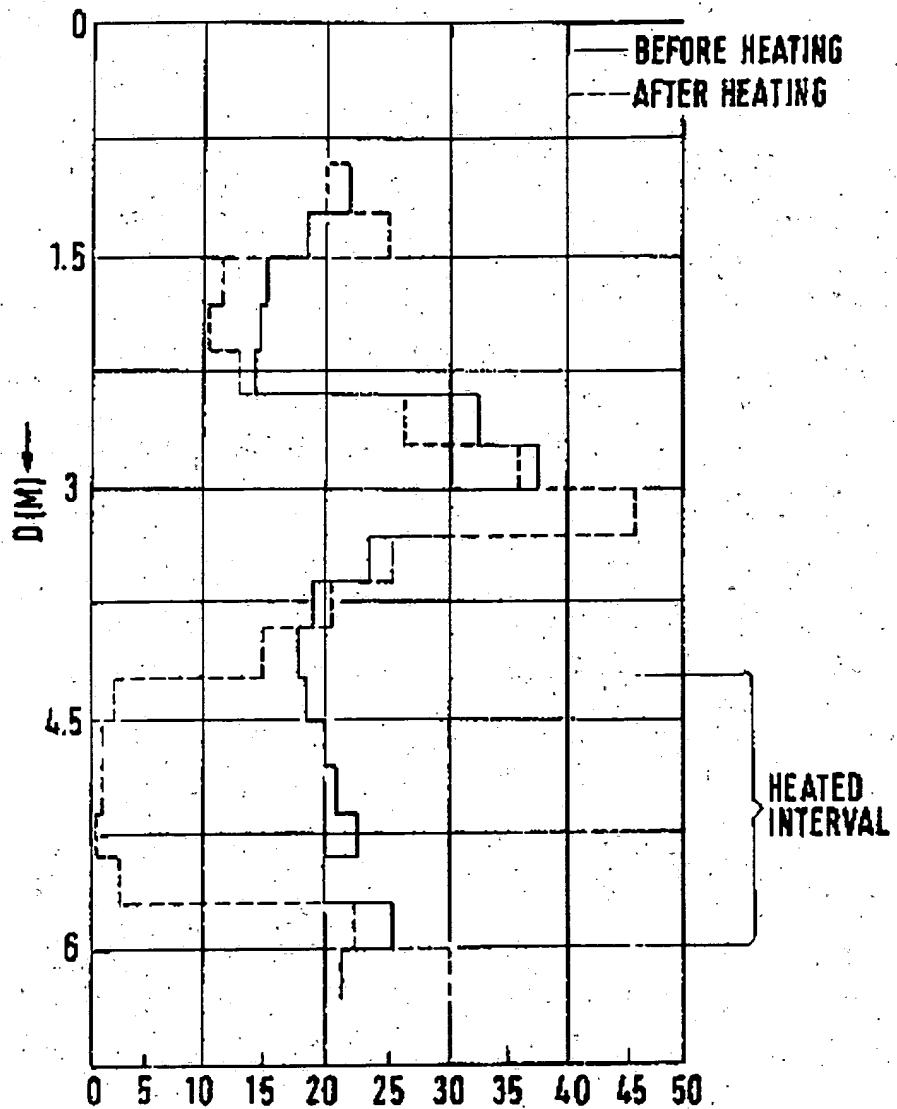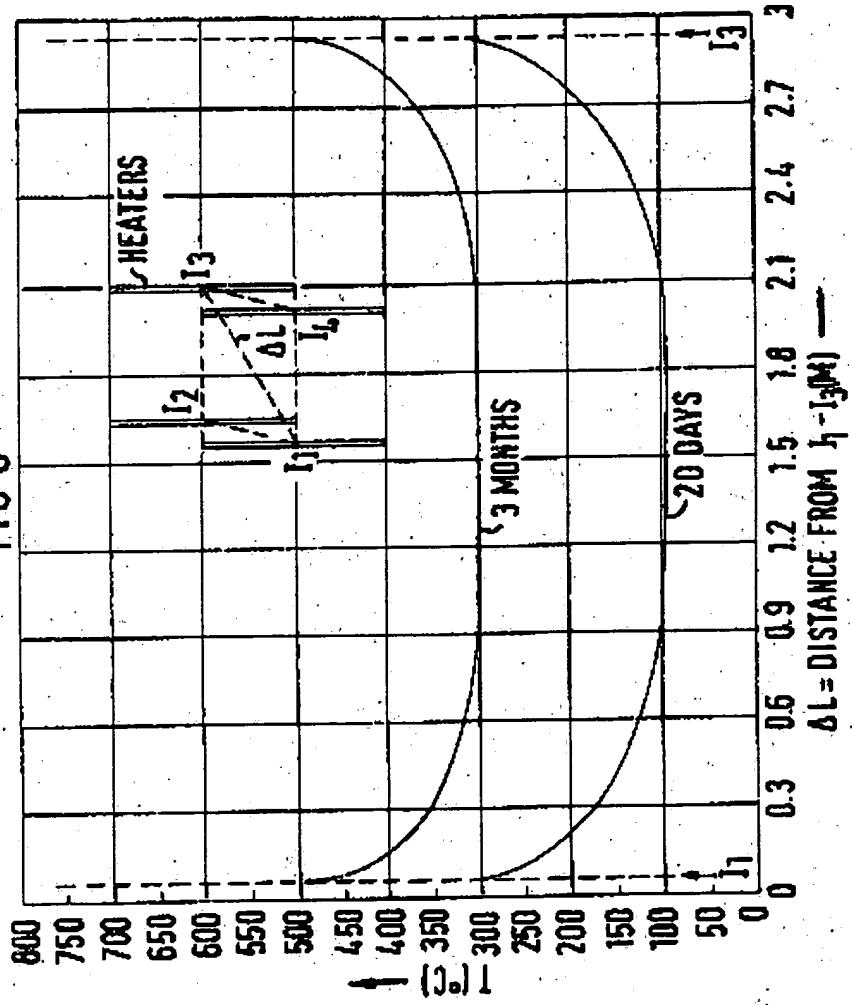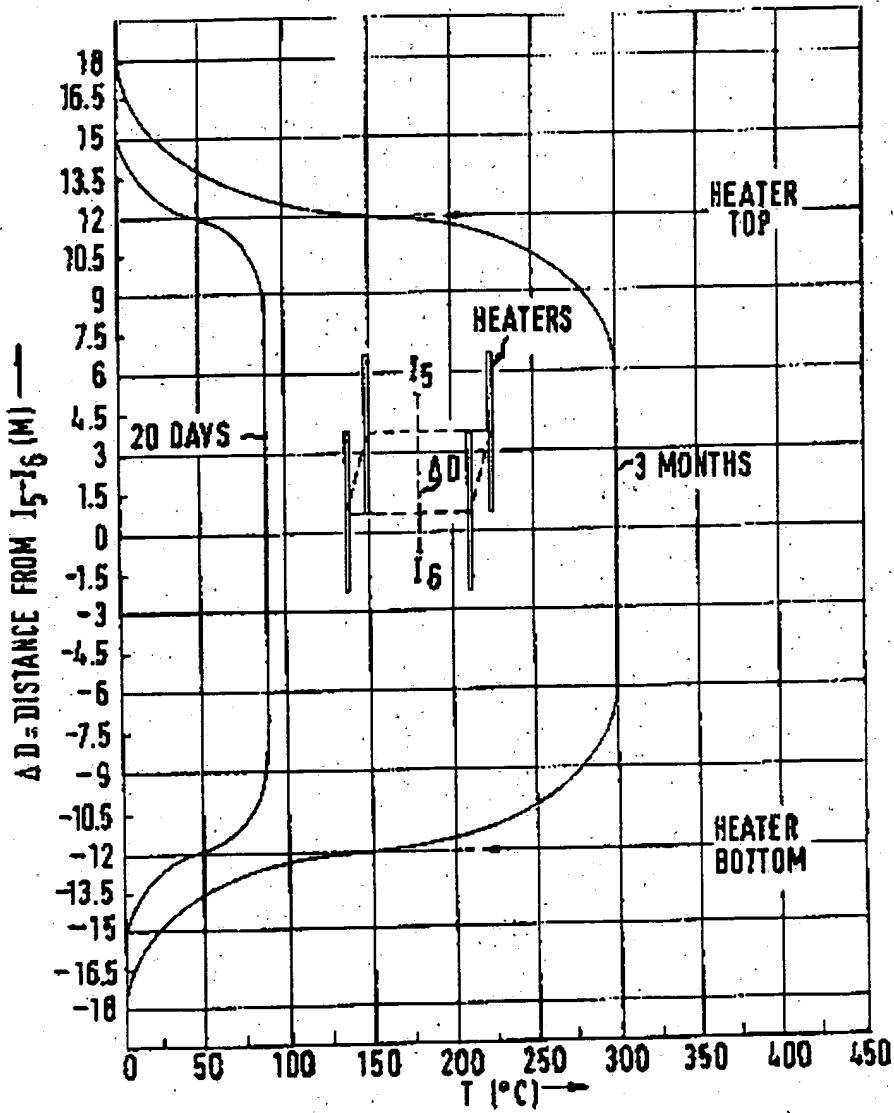
FIG. 7

FIG.7
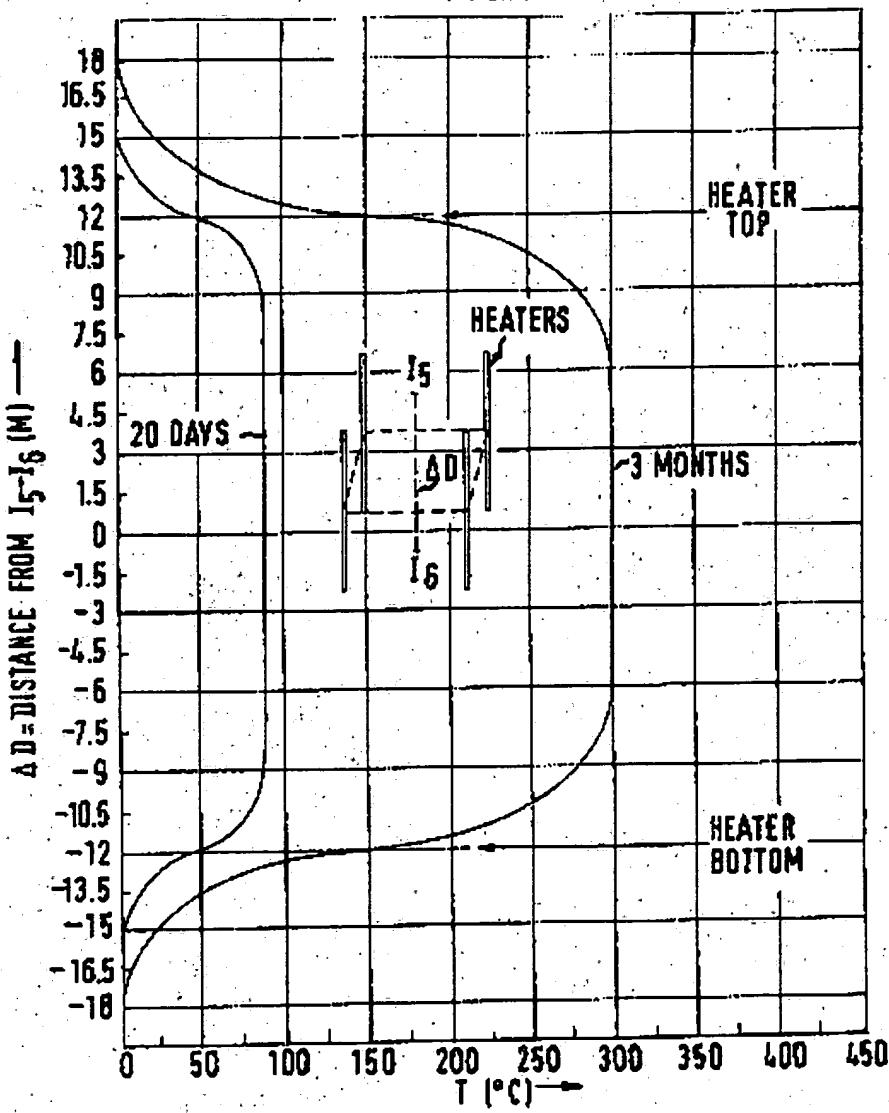
CONDUCTIVELY HEATING A SUBTERRANEAN OIL SHALE TO
CREATE PERMEABILITY AND SUBSEQUENTLY PRODUCE OIL

This invention relates to recovering oil from a subterranean
oil shale by means of a conductive heat drive process. More
particularly, the invention relates to treating a relatively thick,
and substantially completely impermeable subterranean oil shale by
5 means of a conductive heating process which both creates a
permeable zone within a selected portion of the oil shale and
subsequently produces shale oil hydrocarbons.

A permeability-aided type of conductive heat drive for
producing oil from a subterranean oil shale was invented in Sweden
10 by F.Ljungstroem. That process, which was invented about 40 years
ago, was commercially used on a small scale in the 1950s. It is
described in Swedish Patents Nos. 121,737; 123,136; 123,137;
123,138; 125,712 and 126,674, in United States Patent No.
2,732,195, and in journal articles such as: "Underground Shale Oil
15 Pyrolysis According to the Ljungstroem Method", IVA Volume 24
(1953) No. 3, pages 118 to 123; and "Net Energy Recoveries For The
In Situ Dielectric Heating of Oil Shale", Oil Shale Symposium
Proceedings 11, page 311 to 330 (1978). In the Swedish process,
heat injection wells and fluid producing wells were completed
20 within a permeable near-surface oil shale formation so that there
was less than a three-metre separation between the boreholes. The
heat injection wells were equipped with electrical or other heating
elements which were surrounded by a mass of material, such as sand
or cement, arranged to transmit heat into the oil shale while
25 preventing any inflowing or outflowing of fluid. In the oil shale
for which the Swedish process was designed and tested, the
permeability was such that, due to a continuous inflowing of ground
water, a continuous pumping-out of water was needed to avoid
wasting energy by evaporating that water.
30 With respect to substantially completely impermeable,

- 2 -

relatively deep and relatively thick oil shale deposits, such as
those in the Piceance Basin in the United States, the possibility
of utilizing a conductive heating process for producing oil was
previously considered to be -- according to prior teachings and
5   beliefs -- economically unfeasible. For example, in the
above-identified Oil Shale Symposium, the Ljungstroem process is
characterized as a process which "...successfully recovered shale
oil by embedding tubular electrical heating elements within
high-grade shale deposits. This method relied on ordinary thermal
10   diffusion for shale heating, which, of course, requires large
temperature gradients. Thus, heating was very non-uniform; months
were required to fully retort small room-size blocks of shale.
Also, much heat energy was wasted in underheating the shale regions
beyond the periphery of the retorting zone and overheating the
15   shale closest to the heat source. The latter problem is especially
important in the case of Western shales, since thermal energy in
overheated zones, cannot be fully recovered by diffusion due to
endothermic reactions which take place above about 600 °C." (page
313).

20   In substantially impermeable types of relatively thick
subterranean oil shale formations, the creating and maintaining of
a permeable zone through which the pyrolysis products can be flowed
has been found to be a severe problem. In US Patent No. 3,468,376,
it is stated (in cols. 1 and 2) that "There are two mechanisms
25   involved in the transport of heat through the oil shale. Heat is
transferred through the solid mass of oil shale by conduction. The
heat is also transferred by convection through the solid mass of
oil shale. The transfer of heat by conduction is a relatively slow
process. The average thermal conductivity and average thermal
30   diffusivity of oil shale are about those of a firebrick. The matrix
of solid oil shale has an extremely low permeability much like
unglazed porcelain. As a result, the convective transfer of heat is
limited to heating by fluid flows obtained in open channels which
traverse the oil shale. These flow channels may be natural and
35   artificially induced fractures. ... On heating, a layer of

pyrolyzed oil shale builds adjacent the channel. This layer is an inorganic mineral matrix which contains varying degrees of carbon. The layer is an ever-expanding barrier to heat flow from the heating fluid in the channel." The patent is directed to a process for circulating heated oil shale-pyrolyzing fluid through a flow channel while adding abrasive particles to the circulating fluid to erode the layer of pyrolyzed oil shale being formed adjacent to the channel.

Although the thermal conductivity and thermal diffusivity of many subterranean oil shales are, in fact, relatively similar to those of unglazed porcelain and firebrick, US Patent No 3,237,689 postulates that "a rapid advance of a heat front" (Col. 3, line 7) can be obtained by exchanging heat between the oil shale and a nuclear reactor cooling fluid and describes systems for using such reactors either located on the earth's surface or in the oil shale deposit.

US Patent No. 3,284,281 says (at Col. 1, lines 3-21), "The production of oil from oil shale, by heating the shale by various means such as ... an electrical resistance heater ... has been attempted with little success... . Fracturing of the shale oil prior to the application of heat thereto by in situ combustion or other means has been practised with little success because the shale swells upon heating with consequent partial or complete closure of the fracture". The patent describes a process of sequentially heating (and thus swelling) the oil shale, then injecting fluid to hydraulically fracture the swollen shale, then repeating those steps until a heat-stable fracture has been propagated into a production well.

US Patent No. 3,455,383 describes the accumulation of partially depleted oil shale fragments within a flow channel such as a horizontal fracture being held open by the pressure of the fluid within the channel. The patent discloses that if the channel roof is lifted to maintain a flow path above such a layer of depleted shale, the overlying formations must be bent and, without precautions, will bend to an extent causing fractures to extend up

to the surface of the earth. The patent is directed to a process of
intermittently reducing the pressure on the fluid within such as
fracture to allow the weight of the overburden to crush and compact
the layer of depleted shale.

5   In a significant portion of substantially impermeable and
relatively thick oil shale deposits, such as those in the Piceance
Basin, a valuable resource of aluminium is present in the form of
dawsonite. In US Patent No. 3,389,975, directed to recovering
aluminium values from retorted oil shales which have been mined out
10   from such deposits, it is pointed out that, in a substantial
absence of water, at temperatures of about 1300 °F the dawsonite is
converted to crystalline sodium aluminate. Such a water-free
retorting can decompose dolomite in the shale to produce carbon
dioxide, calcite, and magnesium oxide so that magnesium oxide
15   combines with part of the silicon dioxide in the shale, in a manner
permitting a higher recovery of the aluminium values by a leaching
process. US Patent No. 3,502,372, directed to utilizing solution
mining to recover dawsonite, indicates that where the pyrolysis is
effected by an aqueous fluid, such as steam or the products of
20   underground combustion, it must be conducted at a low temperature
and thus relatively slowly, to avoid converting the dawsonite and
other soluble aluminium compounds to an insoluble material such as
analcite. In US Patent No. 3,572,838, a similar relatively low
temperature pyrolysis is alternated with injections of an aqueous
25   alkaline fluid containing an acid-insoluble chelating agent to aid
in leaching dawsonite without forming such insoluble materials.

        The present invention relates to a process for conductively
heating a subterranean oil shale formation in a manner arranged for
producing oil from a subterranean oil shale formation which is,
30   initially, substantially impermeable. In accordance with this
invention, the portion of oil shale deposit to be treated is
selected, on the basis of the variations with depth in the
composition an properties of its components, to have properties
capable of interacting in a manner which enhances the uniformity of
35   the heat fronts to an extent limiting the time and energy

expenditures producing the oil to valu s equivalent to less than
the value of the oil which is produced. The selection of the
treatment interval is based on the grade and thickness of the
portion of oil shale deposit to be treated and the enhancement it
provides amounts to reducing the amount of heat energy lost due to
exothermic side reactions and increasing the amount of oil
recovered from a given grade of oil shale.

In accordance with this invention at least two wells are
completed into a subterranean oil shale treatment interval which
is substantially impermeable, contains substantially no mobile
water, is at least about 30 m thick, is capable of confining fluid
at process pressure, at least substantially within the treatment
interval, and contains a grade and thickness of oil shale such
that the average grade in gallons of oil plus gas equivalent per
ton by Fischer Assay is at least about 10 and the product of the
grade times the thickness in metres of the oil shale is at least
about 900.

Thus, the present invention provides in a process in
which oil is produced from a subterranean oil shale deposit by
extending at least one each of heat-injecting and fluid-producing
wells into the deposit, establishing a heat-conductive fluid-
impermeable barrier between the interior of each heat-injecting
well and the adjacent deposit, and then heating the interior of
each heat-injecting well at a temperature sufficient to
conductively heat oil shale kerogen and cause pyrolysis products
to form fractures within the oil shale deposit through which the
pyrolysis products are displaced into at least one production
well, an improvement for enhancing the uniformity of the heat

fronts moving through the oil shale deposit, which comprises:

- determining variations with depth in the composition and
  properties of the oil shale deposit;

- completing said heat-injecting and fluid-producing wells
  selectively into a treatment interval of oil shale in which
  the oil shale deposit (a) is at least about 30 m thick, (b)
  is substantially impermeable and free of mobile water,
  (c) has a composition and thickness such that the product of
  the average Fischer Assay grade times the thickness of the
  treatment interval is at least about 900, and (d) thereby
  contains components capable of interacting in a manner
  enhancing the uniformity of a front of conductively
  transmitted heat, with said wells being arranged so that,
  at least substantially throughout said treatment interval,
  the well boreholes are substantially parallel and are
  separated by substantially equal distances of at least
  about 6 m; and

- within the interior of each heat-injecting well maintaining
  an average temperature which, selectively along said
  treatment interval, is at least about 600°C, but is not
  high enough to thermally damage equipment within the well,
  while heat is being transmitted away from the well at a
  rate not significantly faster than that permitted by the
  thermal conductivities of the earth formations adjacent to
  the heated interval within the well.

In a location in which a subterranean oil shale may
contain portions which are generally suitable for use as a

treatment interval (as described above) but are apt to be

permeated by substantially disconnected natural fractures and/or

planes of weakness as well as being located near boundaries of the

oil recovery pattern and/or near a potentially active aquifer, the

operation of the present process can advantageously be combined

with a use of "guard wells" located near the periphery of the oil

recovery pattern and/or between a production well and an aquifer.

Such guard wells are extended at least substantially throughout

10 the vertical extent of the treatment intervals and the adjacent

formations are initially heated by thermal conduction in a manner

similar to that employed in the heat-injecting wells, except that

the guard wells are heated at temperatures which are too low to

gasify significant proportion of the oil shale organic components

but are high enough to cause a significant thermal expansion of

the rock matrix of the oil shale deposit.

In some instances, it may be desirable to maintain such

a

relatively low temperature guard well heating throughout at least a
substantial portion of the shale oil recovery process. In other
instances, after an initial relatively low temperature heating of
the guard wells, it may be advantageous to heat guard wells at
5   about the temperature selected for the heat-injecting wells, in
order to expand the pattern of walls from which oil is displaced by
thermal conduction.

As used herein regarding the grade of the portion of oil shale
to be treated, the "average grade in gallons per ton by Fischer
10 Assay" refers to the following: The determination is or is
equivalent to a determination conducted substantially as described
in the ASTM Standard Test Method I) 3904-80. Crushed raw shale is
sampled by riffle-splitting. The determination of the amount of oil
plus gas equivalent available from oil shale is made by heating the
15 raw shale from ambient temperature to 500 °C in cast aluminium-
alloy retorts. The vapours distilled from the sample are cooled and
the condensed fraction is collected. The oil and water fractions
are separated, the water volume (converted to weight equivalent) is
measured and subtracted from the oil plus water weight. The weight
20 of uncondensable gases evolved (gas-plus-loss) is then calculated
by difference. The grade, as used in the "grade times thickness in
metres of oil shale" product, is the gallons of oil plus
hydrocarbon gas equivalent corresponding to the total weight of oil
plus hydrocarbon gas evolved by the heating.

25 The walls are completed into the treatment interval and are
arranged to provide at least one each of heat-injecting and fluid-
producing wells having boreholes which, substantially throughout
the treatment interval, are substantially parallel and are
separated by substantially equal distances of at least about 6 m.
30 In each heat-injecting well, substantially throughout the treatment
interval, the well-surrounding face of the oil shale formation is
sealed with a solid material and/or cement which is relatively heat
conductive and substantially fluid impermeable. In each fluid-
producing well, substantially throughout the treatment interval,
35 fluid communication is established between the well borehole and

the oil shale formation and the well is arranged for producing
fluid from the oil shale formation. The interior of each
heat-injecting well is heated, at least substantially throughout
the treatment interval, at a rate or rates capable of (a)
increasing the temperature within the borehole interior to at least
about 600 °C and (b) maintaining a borehole interior temperature of
at least about 600 °C without causing it to become high enough to
thermally damage equipment within the borehole while the rate at
which heat is generated in the borehole is substantially equal to
that permitted by the heat conductivity of the oil shale formation.

In a preferred embodiment of the present process, the material
for sealing the face of the oil shale formation along the borehole
of at least one heat-injecting well is a closed bottom casing
grouted by cement arranged to fill substantially all of the space
between each outermost metallic element present within the interior
of the borehole and the adjacent face of the oil shale formation,
with said cement having a thermal conductivity at least
substantially as high as that of the oil shale formation.

Determinations are made of variations with depth in the
composition and properties of the oil shale deposit and, in a
particularly preferred procedure, based on the variation with depth
in the heat conductivity of the oil shale deposit, the heat-
injecting wells are heated so that relatively higher temperatures
are applied at depths adjacent to portions of the oil shale deposit
in which the heat conductivity is relatively low. In addition, or
alternatively, in various situations, the effective radius of at
least one heat-injecting well is increased by creating an expanded
portion of the well borehole and extending heat-conducting metal
elements from within the heated well interior to near the wall of
the expanded portion of the borehole.

The present process is valuable for use within a treatment
interval of oil shale which contains other valuable minerals such as
dawsonite and/or nahcolite. In such a situation the present process
creates a permeable zone which is selectively located, within the
treatment interval and substantially within the boundaries of the

well pattern used for the oil production. The resultant permeable
zone is a zone from which such other minerals can be solution-
mined.

In general, the present invention is applicable to
substantially any subterranean oil shale deposit containing an
interval of substantially impermeable oil shale which is
substantially free of mobile water, is more than about 30 m thick,
and has an adequate average grade in gallons per ton (Fischer
Assay) to give a grade-thickness product of about 900 or greater.
The average grade of the heated interval should be greater than
about 10 gallons per ton (Fischer Assay). Within these limitations,
a higher grade-thickness product is increasingly desirable if other
conditions such as depth remain the same.

The invention will now be explained in greater detail with
reference to the accompanying drawings, in which:

Figure 1 shows a plot of relative rate of return (RR) for 1982
US dollars invested in installing and operating the process of the
present invention, as a function of oil shale grade-thickness
(GxTH) product, to produce shale oil at its 1982 value.

Figure 2 illustrates a plot of thermal profiles at an
observation well regarding temperatures measured at different
depths (D) and times within that well.

Figure 3 is a plot of the radial thermal profiles at the
middle of a heated zone after different times of heating.

Figure 4 is a plot of thermal conductivities parallel and
perpendicular to the bedding planes of an oil shale as a function
of temperature.

Figure 5 is a graph of Fischer Assay yield with depth (D) in
and above a heated portion of subterranean oil shale.

Figures 6 and 7 are plots of horizontal and vertical
temperature profiles within a heated portion of subterranean oil
shale formation.

Figure 8 is a schematic illustration of a portion of a well
completion arrangement suitable for practising the present
invention.

well pattern used for the oil production. The resultant permeable zone is a zone from which such other minerals can be solution-mined.

In general, the present invention is applicable to substantially any subterranean oil shale deposit containing an interval of substantially impermeable oil shale which is substantially free of mobile water, is more than about 30 m thick, and has an adequate average grade in gallons per ton (Fischer Assay) to give a grade-thickness product of about 900 or greater. The average grade of the heated interval should be greater than about 10 gallons per ton (Fischer Assay). Within these limitations, a higher grade-thickness product is increasingly desirable if other conditions such as depth remain the same.

The invention will now be explained in greater detail with reference to the accompanying drawings, in which:

Figure 1 shows a plot of relative rate of return (RR) for 1982 US dollars invested in installing and operating the process of the present invention, as a function of oil shale grade-thickness (GxTH) product, to produce shale oil at its 1982 value.

Figure 2 illustrates a plot of thermal profiles at an observation well regarding temperatures measured at different depths (D) and times within that wall.

Figure 3 is a plot of the radial thermal profiles at the middle of a heated zone after different times of heating.

Figure 4 is a plot of thermal conductivities parallel and perpendicular to the bedding planes of an oil shale as a function of temperature.

Figure 5 is a graph of Fischer Assay yield with depth (D) in and above a heated portion of subterranean oil shale.

Figures 6 and 7 are plots of horizontal and vertical temperature profiles within a heated portion of subterranean oil shale formation.

Figure 8 is a schematic illustration of a portion of a well completion arrangement suitable for practising the present invention.

tar sand, Ljungstroem teaches that the in situ heating and
pyrolyzing should be done in a portion of the impermeable formation
which is vertically contiguous to a well-interconnecting fracture
or a layer which has different geological character and is
permeable to flow of the fluid products of the heating or
pyrolysis.

Contrary to the implications of such prior teachings and
beliefs, applicants discovered that the presently described
conductive heating process is economically feasible for use in a
substantially impermeable subterranean oil shale. This is not
obvious, particularly in view of the fact that the present process
uses a much larger well spacing than that used in the Swedish
process and the present process is conducted by heating the
injection wells to temperatures of at least about 600 °C (although
600 °C has been said to be conducive to an economically untenable,
heat-wasting, endothermic reaction; see the Oil Shale Symposium
Proceedings mentioned above).

By means of laboratory and field test measurements and
mathematical models of the present process, applicants have found
that when the wells are spaced, completed, and operated as
presently described, the only region in which heat energy is
utilized in an endothermic reaction amounts to less than about 1%
of the area to be heated, and the energy lost in that fashion is
insignificant. Applicants have measured the rate at which
substantially impermeable oil shale formations are heated by
conductivity, and have determined the amount of heat required for
pyrolysing kerogen and thermally pressurizing the pyrolysis
products to pressures capable of fracturing a relatively deep oil
shale formation and thermally displacing pyrolysis products through
the so-created permeability.

The data obtained by such measurements in the field and in the
laboratory have been employed in calculations of power require-
ments, economics, time to start production, project duration,
amount of production, etc., in mathematical simulations that
correlate with the field and laboratory data and indicate the
magnitudes of such factors in respect to a full scale process.

Those calculations indicate that the presently defined process is the only shale oil production process of which applicants are aware which is capable of economically obtaining oil from a relatively low grade oil shale formation, such as one in which the Fischer

5   Assay is only 15 gallons or less per ton. This capability can increase the petroleum reserves of a significant proportion of the oil shale lands by a factor of six. In addition, with respect to processes for underground mining and modified in situ retorting of oil shale, the present process significantly increases the amount

10   of available resources by eliminating the need for support pillars and interburden between mining zones and by providing a means for treating substantially all of a very thick interval of oil shale.

The present process can advantageously be applied to an oil shale formation in which there is significant concentration of a

15   mineral such as dawsonite or nahcolite. In such a formation the process provides a permeable zone from which such a mineral can be recovered. In addition, the present process is particularly advantageous in converting dawsonite to water-soluble compounds of aluminium (probably rho-alumina) which have been (both chemically

20   and physically) made available for solution-mining to produce the aluminium -- an essential material which is in short supply within the United States. In contrast to many previously proposed processes, the process of the present invention requires substantially no water, involves minimal land disruption, and can be

25   conducted with minimal atmospheric pollution.

Figure 1 shows the relative rate of return for 1982 US dollars invested in installing and operating the present process in field applications that have been mathematically modelled from data obtained by field and laboratory measurements.

30   EXAMPLE 1

A series of injection and production wells is drilled into an oil shale formation 40 m in thickness with 120 m of overburden. The average oil grade of the interval is 20 gallons per ton as determined by Fischer Assay.

35   The well pattern is a seven-spot with each heat injector at

the corner of a regular hexagon surrounding a central producing
well. The spacing is 22.5 m between producers and injectors. The
pattern repeats with producers sharing the injectors in each
direction and continues to form a field-wide pattern capable of
producing a large quantity of oil. The injector-to-producer ratio
approaches 2 to 1 in a large field. In Example 1 the total oil
production is 25,000 barrels per day throughout the life of the
project.

The injection wells electrical heaters are cemented into the
formation and connected to a power source on the surface. The
production wells are equipped with standard oil field pumps for
lifting the produced oil to the surface. The electrical injection
rate is 3.23×10^6 BTU/well per day. The temperature of the
injectors attains 750 °C. The production wells reach a terminal
temperature of 300 °C after 33-34 years of operation. Production
over this period averages 5-6 barrels/day per well, with the
average number of active producing wells being from about 4000 to
5000. Heat consumption is 1.1×10^6 BTU/barrel of liquid oil
production.

Gaseous products collected from the production wells may be
used for on-site generation of electricity or other purposes. The
oil-phase petroleum which is so produced is superior to con-
ventionally retorted shale oil. The relative rate of return which
can be expected from the Example 1 situation is illustrated by the
"Ex. 1" situation designation on Figure 1.

EXAMPLE 2

A series of injection and production wells are drilled into an
oil shale formation 225 m in thickness with 300 m of overburden.
The average grade of the oil shale interval is 26 gallons per ton
as determined by Fischer assay.

The well pattern is the same seven-spot described in Example 1
except the spacing is 13.5 m between walls instead of 22.5 m. Total
production is 25,000 barrels/day throughout the life of the project.
The injector to producer ratio still approaches 2 to 1. In the
wells, the heaters and production equipment are similar to those
described in Example 1.

The electrical injection rate is 10.55×10^6 BTU/well per day. The injection well temperatures reach 750 °C and the production wells reach a final temperature of 300 °C after a production life of 9-10 years. Production over this period averages 42-43 barrels/day per well, with the average number of active producing wells being about 600. The heat consumption is 5.6×10^5 BTU/barrel of liquid oil produced.

As in Example 1, gaseous products can be used for on-site power generation or other purposes and the liquid product will be higher in quality than conventionally retorted shale oil. The relative rate of return which can be expected is illustrated by the "Ex. 2" situation designation on Figure 1.

Table 1 lists combinations of oil, shale grades, thicknesses and grade-thickness products which are generally suitable for use in the present process. The relative positions of such grade thickness products with respect to the relative rates of financial return are illustrated by the designations "Preferred Range" (P.R.) and "Especially Preferred Range" (E.P.R.) on Figure 1.

TABLE 1

Grade (gallons/ton)	Thickness (m)	Grade x Thickness
30	30	900
20	45	900
10	90	900

More desirable grade thickness examples are shown as follows:

Grade (gallons/ton)	Thickness (m)	Grade x Thickness
30	150	4500
25	60	1500
20	300	6000
15	600	9000
10	225	2250

In general, the higher the grade thickness product the more desirable. The practical application is limited only by the ability to heat the desired interval.

Field Test Measurements

Tests were conducted in an outcropping of an oil shale formation which is typical of substantially impermeable and relatively thick oil shale deposits. Thirteen boreholes were drilled to depths between 6 and 12 m and were arranged to provide a pattern of heat-injection, observation and fluid-production wells, with the boreholes being spaced about 0.6 m apart in order to provide a relatively rapid acquisition of data. Heat was injected at a rate of about 1000 watts per metre for five days. After the heat-injection wall temperature had reached 450 °C, a temperature fall-off test was run for one day.

Figure 2 shows the vertical thermal profiles in an observation well, as a function of time. The data was fitted to a mathematical solution describing the temperature distribution around a finite-length line source inside a medium of thermal conductivity (parallel to bedding) 3.25 mcal/cm-sec-°C and thermal conductivity (perpendicular) 3.25 mcal/cm-sec-°C. The specific heat capacity utilized in the calculations was computed from the thermal conductivity, thermal diffusivity, and average bulk density of cores recovered during drilling of the wells. The thermophysical properties for the the oil shale in which the tests were conducted are summarized in Table 2.

TABLE 2

Initial Reservoir Temperature	9.8 °C
Fischer Assay:	20 gallon/ton
Bulk Density:	2.20 gm/cm^3
Thermal Diffusivity:	6.6 × 10^{-3} cm^2/sec
Specific Heat Capacity:	0.224 cal/gm °C

Figure 3 shows radial profiles computed for the middle of the heated zone for various heating times (t). At the end of a temperature build-up test of 140.5 hours, the average formation temperature between the heater and observation well was 120 °C.

Figure 4 shows a comparison of laboratory values and field
data relative to the thermal conductivity parallel to and
perpendicular to the bedding planes of the oil shale formation, as
a function of temperature. The laboratory conductivity measurements
were made on adjacent samples of cores from the observation well,
using some cores cut parallel to and some cut perpendicular to the
bedding planes. A nitrogen-atmosphere was used to eliminate
oxidation reaction. The samples were constrained in the vertical
direction but were free to expand radially. After the samples were
heated to 800 °C, the radial expansion averaged 1.45%. As shown in
the figures, the laboratory values are in excellent agreement with
the values computed from the field data. The tests indicate that
the thermal conductivity is lower in the direction perpendicular to
the bedding plane, because kerogen layers have a lower conductivity
than the dolomite matrix. At temperatures below 100 °C, the thermal
conductivity is essentially isotropic, as observed in the field
tests. But, that conductivity becomes increasingly anisotropic, as
the kerogen is removed (at temperatures between 300 and 400 °C) and
gas begins to occupy the spaces between the layers. Above 700 °C,
both the parallel and perpendicular conductivity decrease sharply
due to the decomposition of the dolomite and evolution of CO_2.

When a subterranean oil shale formation is heated the oil
shale expands as the temperature increases. When the oil shale
temperature reaches a kerogen pyrolyzing temperature (for example,
from about 275-325 °C) additional expansion forces are generated.
The kerogen is converted to fluids capable of occupying a larger
volume than the kerogen, and such fluids become increasingly
pressurized when the temperature is increased. As more fluid is
formed and more fluid is heated, hydraulically induced fractures
form within the oil shale formation.

Fractures which are hydraulically induced within subterranean
earth formations form along planes perpendicular to the least of
the three principal compressive stresses (i.e., one vertical and
two mutually perpendicular horizontal compressive stresses) which
exist within any subterranean earth formation. However, where the

hydraulic fractures tend to be vertical, horizontal fractures can
be formed by injecting heated fluids so that the walls of the
vertical fractures are heated until they swell shut. Then, by
increasing the fluid injection pressure to greater than overburden
5   pressure, a horizontal fracture can be formed. Such processes for
thermally inducing the formation of horizontal fractures by
injecting externally heated and pressurized fluids are described in
patents such as the above-mentioned US Patent No. 3,284,281; US
Patent No. 3,455,391 by C.E. Matthews, P. Varneure and C.W. Volek,
10   and US Patent No. 3,613,785 by P.J. Closmann.

Applicants have now discovered that when substantially
impermeable subterranean oil shales having the presently specified
combination of grade and thickness were conductively heated as
presently specified, a zone of permeability was developed between
15   wells within the oil shale. Although the present invention is not
premised on any particular mechanism, in the course of such a
treatment the heated oil shale behaved as though it was subjected
to the above-described type of process for thermally inducing the
formation of horizontal fractures. Such a behaviour was not
20   predictable, since the present process is operated without any
injection of any fluid. It appears that when the present process is
operated within an impermeable oil shale, the in situ generation
and displacement of heated and highly pressurized fluids occurs at
the times and to the extents needed to successively extend and
25   horizontally fracture through successive portions of the oil shale,
when those portions become conductively heated. The zone being
heated appears to undergo a relatively uniform, horizontal, radial
expansion through the oil shale, at the rate set by the thermal
conductivity of the oil shale. In each successive location in which
30   a kerogen pyrolyzing temperature is reached, fluids appear to be
formed, heated and pressurized so that substantially any vertical
fractures which are formed within the heated zone are subsequently
converted to horizontal fractures.

Applicants' tests indicated that substantially all of the
35   fluid pyrolysis products of the oil shale tended to remain in or

near the locations in which they were formed until they were
displaced, through substantially horizontal fractures, into wells
adjoining the heat-injecting wells. In addition, the fracture-
inducing pressure of fluids in the horizontal fractures appears to
have been reduced as those fluids expanded and were cooled as they
moved away from the hottest portions of the heated zone.

Thus, the present process seems to induce the moving of a zone
of kerogen-pyrolyzing temperatures through the oil shale
immediately behind a zone of localized fracturing in which the
fractures are, or soon become, horizontal fractures. The heating
and fracturing zones seem to undergo a substantially uniform,
horizontal, radial expansion through the oil shale, until the zone
of fracturing reaches a location (such as the borehole of a
production well) from which the oil shale pyrolysis products are
withdrawn.

In addition, applicants have discovered that, at least where
the overburden pressure is small, the zone of permeability that is
created between adjacent walls retains a significantly high degree
of permeability after the formations have cooled. Thus it appears
that, even if the overburden pressure is high, an application of
the present process is capable of forming a well-interconnecting
zone in which the permeability remains high or can be readily
restored by an injection of fluid after some or all of the heat has
dissipated. And, the degree and location of that permeability can
be controlled by controlling the rate of removing fluid from the
producing walls.

The data obtained by measurements in field tests of the type
described above were inclusive of: the thermal conductivity of the
oil shale formation, the amount of oil recoverable by Fischer
analysis at various depths within heated intervals of the oil shale
before and after heating, the measurement of the amount of
pyrolysis products recovered, and the like. While no communication
existed between heat injectors and producers at test start-up,
injections at the end of the test demonstrated that permeable
channels had formed. The results of standard engineering

calculations were indicative of the applicability of a concept of
the type described above to the results obtained by the tests.

Figure 5 is a graph of Fischer Assay yields, from the target
zone in the field test, as a function of depth 0. The heated
interval extended from 4.2 to 6 m. The solid curve shows the yields
before the heating treatment and the dashed curve shows the yields
after retorting was completed. The yields before and after were
essentially the same outside the heated interval. The measurements
were made on cores from the centre of the pattern before heating
and on cores about 15 cm away after heating. The variations which
are apparent in those yields are within the normal limits of
accuracy for the measuring of such values.

Within the heated interval the Fischer Assay yield drops from
an average of 20 gallons/ton before the test to less than 2
gallons/ton after heating. The retorting efficiency within the
process zone was thus better than 90% of Fischer Assay.

The pattern and extent of the recovery confirms the fact that
little oil was lost over the producing horizon through vertical
fractures. In addition, the uniformity in retorting efficiency
through the heated zone, indicates that thermal fronts were
approximately uniform over most of the heated interval.

The uniformity of the thermal fronts is even more apparent in
Figures 6 and 7. They show horizontal and vertical temperature
profiles calculated for a set of vertical heaters in a five-spot
square pattern. The set used in the calculations included four heat
injectors and one centre producer (not shown, but centered between
the heaters shown on the figures). Each heater was assumed to be
24 m long and heated at the rate of 814 W/m.

The profiles in Figure 6 (graphs of temperature variations
with distances from the heaters) were calculated along a horizontal
segment I_1I_3 which extends through the mid-points of heaters at
opposite corners of the square. Figure 7 is a similar graph of
profiles along a vertical segment I_5I_6 on the axis of symmetry of
the pattern.

Such calculations indicate that by the time retorting

temperatures (275-325 °C) are reached at the centre of the pattern,
more than 87% of its volume has been converted while only about 14%
of the converted volume was heated to more than 325 °C. Furthermore,
the calculations indicate that if the power is turned off or
reduced before the centre reaches a target temperature such as
325 °C, the levelling off of the thermal fronts will still heat the
centre of the pattern to retorting temperatures and will also
reduce the temperature rise at the heaters. This mode of operation
can ensure that less than 10% of the heated volume is heated to
more than 325 °C, and thus can increase the thermal efficiency of
the process.

In view of the above test results and the calculations based
on those results, it appears that, contra to the prior teachings
and beliefs, the initial impermeability of an oil shale deposit can
be utilized as an advantage. The initial impermeability confines
the fluids and fractures within the well pattern, since no
permeability exists until the zone between the heat-injecting and
fluid-producing wells become permeated by a pattern of heat-induced
horizontal fractures.

In the present process, the rate at which heat is transmitted
into the oil shale deposit is strongly affected by the temperature
gradient between a heat-injecting well and the surrounding earth
formation. In a preferred procedure, the determinations of
variations with depth in the composition and properties of the oil
shale deposit include a determination of the pattern of heat
conductivity with depth within the earth formations adjacent to the
heat-injecting well. Based on such determinations the temperatures
to which at least one heat-injecting well is heated are arranged to
be relatively high at the depths at which the heat conductivities
of the adjacent earth formations are relatively low. This tends to
cause the rate at which heat is transmitted through the earth
formations to be substantially uniform along the axis of the
heat-injecting well. Known procedures can be utilized in order to
provide higher temperatures in portions of heat injecting wells
adjacent to earth formations of relatively low heat conductivity.

For example, in wells which are being heated by electrical
resistances, additional resistant elements can be positioned at
the location at which extra heating is required, preferably with
precautions being taken to avoid the creation of "run-away hot-
spots" due to increasing temperature further increasing the
resistance and thus further increasing the heating, for example,
as described in the commonly assigned Canadian patent application
Serial No. 495,854 filed November 21, 1985, by P. VanMeurs and
10   C.F. Van Egmond. In wells being heated by combustion, more, or
larger, or more heavily fired, burner elements can be positioned
in such locations.

        Suitable determinations of compositions and properties
of the minerals and/or organic components of an oil shale deposit
and the variations with depth in such properties can be made by
means of known well logging, reservoir sampling, and the like
analytical procedures. The determinations can utilize previously
measured geophysical or geochemical data or laboratory or core
analyses, etc. For example, the variations with depth in the heat
20   conductivity of the adjacent formations can be determined by
calculations based on the kinds and amounts of materials present,
and/or by thermal conductivity logging measurements, etc. US
Patent No. 3,807,227 describes a logging tool containing a
constant output heat source and three temperature sensors for
obtaining a log of relative thermal conductivity with depth. US
Patent No. 3,892,128 describes logging cased or open boreholes for
temperature, specific heat and thermal conductivity, employing a
constant output heat source and three temperature sensors. US

Patent No. 3,864,969 describes a logger for making station measurements of thermal conductivity by heating a formation for a time then measuring the rate at which the temperature decays back to the ambient temperature. US Patent No. 3,981,187 describes logging thermal conductivity of a cased well by measuring the temperature of the casing wall before and after passing a heated probe along the well.

      As indicated above, even with respect to a five-spot pattern in which a single fluid-producing well is surrounded by four heat-injecting wells, substantially all of the intervening oil

shale can be both retorted and made permeable. However, the present
invention is preferably employed in a series of contiguous seven-
or thirteen-spot patterns -- in either of which patterns
(particularly in the thirteen-spot pattern) the retorting rate is
significantly increased by having each fluid-producing well
surrounded by six or twelve heat-injecting wells.

The wells used in the present process can be completed by
substantially any method for drilling a borehole into and/or
opening a pre-existing borehole into fluid communication with the
subterranean oil shale formation to be used as an oil shale
treatment interval. In addition to having the specified absence of
significant amounts of mobile water, thickness, and grade of oil
shale, the interval to which the present process is applied should
be capable of confining fluid at least substantially within the
treatment interval, at least in respect to allowing no significant
leakage into overlying locations when the pressure of the fluid
reaches process pressure, and fractures the formation within the
treatment interval. The boreholes of wells completed for use in the
present process should be substantially parallel and separated by
substantially equal distances of at least about 6 m. Borehole
separation distances between injectors and producers of from about
9 to 30 m are particularly suitable. Boreholes free of deviations
from parallel which cause variations of more than about 20 per cent
of the well distances are particularly suitable.

In the heat-injecting wells used in the present process, the
cement or cement-like material which is used to seal along the face
of the oil shale formation is preferably relatively heat-conductive
and substantially fluid-impermeable. Particularly preferred cements
are stable at temperatures of at least about 800 °C, have a
relatively high thermal conductivities, relatively low permeability,
little or no shrinkage, an adequate ease of pumpability and good
chemical resistance, etc. The permeability and disposition of the
sealing material should provide a seal capable of preventing any
significant amount of fluid flow between the interior of the
borehole and the face of the oil shale formation, so that the

transfer of heat from the wall to the formation is substantially
entirely by conduction. Where portions of the heat-injecting wall
borehole are effectively increased in diameter near upper and lower
extremities of the treatment interval, for example, by under-
reaming, the diameters of the increased portions are preferably at
least about 110% of the nominal borehole diameter. Calcium
aluminate-bonded concretes and/or cements containing alumina-
silicate aggregates (or fine particles) are particularly suitable
for use as such formation face-sealing materials. Examples of
suitable cements and concretes include those described in US
patents such as 3,379,252; 3,507,332 and 3,595,642.

Figure 8 shows a portion of a heat-injecting well borehole,
borehole 1, which is suitable for use in the present invention and
is located within a treatment interval of subterranean oil shale
deposit. Borehole 1 contains enlarged portions, such as portions 2
and 3, which can be formed by conventional procedures such as
underreaming during drilling, etc. A casing 4 is shown positioned
within the borehole and cemented into place with a fluid-
impermeable, heat-conductive material, such as cement.

Within each enlarged borehole portion, the casing 4 is
equipped with at least one heat-conductive metal element, such as
collar 6, containing radially extensive elements or portions, such
as flexible metal members 7. Such heat-conductive materials form
relatively highly conductive paths for conducting heat from within
the interior of a borehole to substantially the wall of an enlarged
portion of the borehole. Examples of suitable heat-conductive metal
elements include metal wall scratchers, turbulence inducers,
centralizers and the like such as a Hammer-Lok Turbobonder, or
Boltlok Turbobonder, available from Bakerline division of Baker Oil
Tools or a 101 Bar S centralizer available from Antelope Oil Tool
and Manufacturing Company, etc.

With an arrangement of the type shown in Figure 8, at least to
some extent, the front of heat transmitted away from a heat-
injecting well can be made more uniform along a vertical line
traversing a layer of relatively low heat conductivity without the

necessity of maintaining a higher temperature in the portion of the
well adjacent to that layer. When a uniform temperature is
maintained within the interior of the borehole, the earth formation
face along such an enlarged portion of the borehole becomes heated
to substantially the same temperature as the formation face along
narrower portions of the borehole. Since the face of the formation
adjoining the borehole is heated to the highest temperature of any
portion in the formation, the temperature gradient extending
radially away from the enlarged portion of the boro-hole is shifted
radially away from the borehole.

In general, the heating of the interior of the heat-injecting
well can be accomplished by substantially any type of heating
device, such as combustion and/or electrical type of heating
elements, or the like. The heating element should extend
substantially throughout the treatment interval (preferably
throughout at least about 80 per cent of that interval). Where a
combustion type heating element is used, a gas-fired heater is
preferred. The fuel and oxidants for a combustion heater (such as
methane and oxygen) are preferably supplied trough separate
conduits leading through a heat exchanger in which the incoming
fluids are heated by the outflowing combustion products. The burner
housing and fluid conduits of a combustion heater are preferably
installed within a well conduit which is surrounded by an annular
space that is filled by the cement for sealing the face of the oil
shale. Generally suitable types of combustion heaters which could
be arranged for use in the present process are described in US
Patents such as 2,670,802; 2,780,450 and 2,902,270.

An electrical resistance heater is particularly suitable for
heating the interior of a heat-injecting well in the present
process. A plurality of resistance elements are preferably used.
The resistance elements can be mounted within or external to an
internal conduit or rod, or simply extended into the borehole. When
the resistances are external to, or are free of a supporting
element, such as a conduit or rod, they are preferably embedded in
the cement which seals the face of the oil shale along the

treatment interval. Generally suitable types of electrical heaters
which could be arranged for use in the present process are
described in US Patents such as 2,472,445; 2,484,063; 2,670,802;
2,732,195 and 2,954,826.

In various reservoir situations, portions of an oil shale
deposit which would, in general, be suitable for use as a treatment
interval, as described in our parent application, may be permeated
by natural fractures and/or planes of weakness. Such relatively
weak rocks may undergo relatively long extensions of vertical
fractures when pressurized fluids being displaced away from an
injection well move into them. This may result in extending fluid
passageways beyond the openings into production wells and/or into
adjacent aquifers capable of causing an inflow of water to an
extent detrimental to the oil recovery process.

We have now discovered that such premature fracture extensions
can be avoided by drilling and heating "guard wells" within such
relatively weak oil shale zones in locations surrounding a pattern
of heat injecting and fluid producing wells and/or in locations
intermittent between a heat injecting or fluid producing well and
an adjacent aquifer. Such guard wells are used for conductively
heating the adjoining formations substantially throughout the oil
shale interval to be treated to a temperature which is too low to
gasify significant proportions of the oil shale organic components
but is high enough to cause a significant thermal expansion of the
rocks. When those rocks are heated the natural fractures are kept
closed and the fracturing caused by the approaching pressurized
fluids (displaced away from heat-injecting wells) tends to be
limited to horizontal fractures concentrated along the sides nearest
to the heat-injecting wells. Where fluid producing wells are
located substantially between the heat-injecting wells and the
guard wells, the fractures are preferentially extended into those
wells, where the high fluid pressures are quickly reduced by the
production of the inflowing fluid.

The encountering of such relatively weak reservoir rocks is
apt to be indicated by an inflow of water into wells drilled into

such rocks. In general, the natural fractures creating a relative
weakness and/or water inflow can be thermally closed by a
relatively mild heating, as long as the fracture porosity is not
more than about 5 per cent.

C L A I M S

1.   In a process in which oil is produced from a subterranean oil
shale deposit by extending at least one each of heat-injecting and
fluid-producing wells into the deposit, establishing a heat-
conductive fluid-impermeable barrier between the interior of each
5   heat-injecting well and the adjacent deposit, and then heating the
interior of each heat-injecting well at a temperature sufficient to
conductively heat oil shale kerogen and cause pyrolysis products to
form fractures within the oil shale deposit through which the
pyrolysis products are displaced into at least one production well,
10   an improvement for enhancing the uniformity of the heat fronts
moving through the oil shale deposit, which comprises:
-    determining variations with depth in the composition and
properties of the oil shale deposit;
-    completing said heat-injecting and fluid-producing wells
15   selectively into a treatment interval of oil shale in which
the oil shale deposit (a) is at least about 30 m thick, (b) is
substantially impermeable and free of mobile water, (c) has a
composition and thickness such that the product of the average
Fischer Assay grade times the thickness of the treatment
20   interval is at least about 900, and (d) thereby contains
components capable of interacting in a manner enhancing the
uniformity of a front of conductively transmitted heat, with
said wells being arranged so that, at least substantially
throughout said treatment interval, the well boreholes are
25   substantially parallel and are separated by substantially
equal distances of at least about 6 m; and
-    within the interior of each heat-injecting well maintaining an
average temperature which, selectively along said treatment
interval, is at least about 600 °C, but is not high enough to
30   thermally damage equipment within the well, while heat is
being transmitted away from the well at a rate not signi-

ficantly faster than that permitted by the thermal con-
ductivities of the earth formations adjacent to the heated
interval within the well.

2. The process of claim 1 in which, to the extent required to
keep the rate at which heat is transmitted through the oil shale
deposit substantially uniform along the axes of the heated interval
of the heat-injecting well, the temperature at which at
least one heat-injecting well is heated is relatively higher at
depths adjacent to portions of the oil shale deposit in which the
heat conductivities are relatively lower.

3. The process of claim 1 in which the rate of heating the
interior of at least one heat-injecting well is varied to an extent
causing an effective levelling off of the thermal front so that the
rate of advance through the oil shale of the thermal front is
continued at substantially the same rate while the rate of increase
of the temperature within the borehole is significantly reduced.

4. The process of claim 1 in which the heat-injecting and
fluid-producing wells are arranged in a series of contiguous
patterns in which each fluid-producing well is surrounded by at
least four heat-injecting wells.

5. The process of claim 4 in which each fluid-producing well is
surrounded by twelve heat-injecting wells.

6. The process of claim 1 in which the oil shale grade is at
least about 20 gallons per ton and the grade-thickness product is
at least about 4500.

7. The process of claim 1, comprising the steps of
- in each heat-injecting well, substantially throughout the
treatment interval, sealing the face of the oil shale formation
with a solid material which is relatively heat-conductive and
substantially fluid impermeable;
- in at least one heat-injecting well increasing the effective
diameter of the borehole in at least one portion of the treatment
interval and extending at least one heat-conductive metal element
from within the interior of the borehole to near the face of the
so-enlarged portion of the borehole; and
- in each fluid-producing well, substantially throughout the
treatment interval, establishing fluid communication between the

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well bore and the oil shale formation and arranging the well for
producing fluid from the oil shale formation.

8.   The process of claim 7 in which the material sealing the face
of the oil shale formation along the borehole of a heat-injecting
well is a cement arranged to fill substantially all of the space
between the outermost metallic elements within the interior of the
borehole and the face of the oil shale formation, with said cement
having a thermal conductivity at least substantially as high as
that of the oil shale formation.

9.   The process of claim 1 in which at least one well located near
an edge of a pattern of heat-injecting and fluid-producing walls is
extended substantially throughout the treatment interval and heated
at a temperature high enough to cause a thermal expanding and/or
compressive stressing of the adjacent earth formations but low
enough to avoid significant thermal mobilization of organic
components of the oil shale.

10.   The process of claim 9 in which at least one so heated well is
subsequently heated at about the temperature selected for the
heating of the heat-injecting wells being employed.

11.   The process of claim 1 in which the well boreholes of said
heat-injection and fluid producing wells are separated by
substantially equal distances of about 9 to 30 m.

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A B S T R A C T

CONDUCTIVELY HEATING A SUBTERRANEAN OIL SHALE TO
CREATE PERMEABILITY AND SUBSEQUENTLY PRODUCE OIL

Shale oil is subsequently produced from a subterranean
interval of oil shale, where the interval is initially
substantially impermeable and contains a specified grade and
thickness of oil shale. Said interval is conductively heated from
borehole interiors which are kept hotter than about 600 °C and are
heated at a rate such that kerogen pyrolysis products formed within
the oil shale create and flow through horizontal fractures which
subsequently become extended into fluid-producing wells that are
positioned in specified locations.